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The Role of Semiconductor Inputs in IT Hardware Price Decline

Computers versus Communications

Ana Aizcorbe, Kenneth Flamm, and Anjum Khurshid

12.1 Introduction

Since at least the mid-1980s, economists have toiled steadily at improving price indexes for high-tech goods and services. The first fruits of this effort were seen in computers.[1] The use of quality-adjusted price indexes (primarily hedonic price indexes) for computing equipment has now been institutionalized in the national income accounts of the United States and other industrialized nations and has radically altered our understanding of the macroeconomics of growth and productivity improvement over the last two decades.[2]

As evidence from these studies accumulated, it also became clear that

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1. There are now many studies of quality adjustment in computer prices. For an early synthesis of the literature, see Triplett (1989); for a review of more recent work, see Berndt and Rappaport (2001).

2. See, for example, Jorgenson (2001) for one influential reassessment of the impact of IT on U.S. productivity growth.

much of the improvement in computer price performance was based on even more impressive rates of decline in quality-adjusted prices for semiconductors, the major input to computer manufacture.[3] Much recent literature now suggests that changes in semiconductor prices have been a major driver of changes in quality-adjusted computer prices and, even more generally, other types of information technology (IT). Moreover, many have linked an observed quickening in the pace of price declines for semiconductors to an upsurge in the price-performance improvement for IT and ultimately to the improvement in U.S. productivity growth that occurred beginning in the mid-1990s.[4]

Juxtaposed against this backdrop, it is almost startling to discover that in communications equipment, an equally high-tech product and a similarly ravenous consumer of semiconductor inputs, economic studies have documented vastly lower rates of decline in quality-adjusted price over the same periods in which computer prices have been studied closely. This gap between price declines in computers and communications equipment has been both large and long-lived. The earliest known study of price declines in communications equipment showed quality-adjusted prices for small telephone switches actually *increasing* over the period 1970 to 1983, prior to the breakup of the old Bell System monopoly.[5] By contrast, personal computer (PC) prices over the 1976 to 1983 period have been estimated to have been declining at a rate of about 18 percent per year, and mainframe computers to have fallen at roughly similar rates![6]

After divestiture and the breakup of the Bell System in the mid-1980s, the pace of innovation in communications equipment seems to have turned up sharply, but still fell far short of developments in computers. Hedonic estimates of quality-adjusted prices for telephone switches using different data sources, product mixes, and time periods show price declines of about

3. For early calculations suggesting that computer price-performance improvement was due largely to quality-adjusted price changes in electronic components used in computers, see Flamm (1989, 1999). Triplett (1996) constructs an economic framework that, with plausible values, suggests that most of the improvement in computer price performance is due to semiconductors; indeed, he has calculated that multifactor productivity (MFP) for computers is modest, once the contribution of semiconductors has been removed. The first studies of quality-adjusted prices for semiconductor devices were Dulberger (1993), Flamm (1993), and Norsworthy and Jang (1993). More recent work has provided formal modeling and econometric estimation of learning curves (Irwin and Klenow 1994; Flamm 1996) and demand structures (Song 2003) for these devices.

4. For studies suggesting a link between productivity growth and IT quality-adjusted price declines in the productivity speed-up of the 1990s, see Oliner and Sichel (2000), Jorgenson and Stiroh (2000), and Jorgenson (2001). See Flamm (2001) for a detailed analysis of the technical and economic roots of more rapid decline in semiconductor prices as well as an argument that the extraordinary declines in chip prices in the late 1990s must ultimately fall back to a more sustainable pace in the long run. But note that others have expressed some skepticism on the connection between IT price-performance improvement measures and productivity; see Gordon (2000) and Aizcorbe, Oliner, and Sichel (2003).

5. See Flamm (1989).

6. See Berndt and Rappaport (2001) and Cole et al. (1986).

9–12 percent annually (for small rural telephone switches, over the period 1982 to 1985), and 9 percent annually (all telephone switches, over 1985 to 1996).[7] This contrasts with an average annual decline in PC prices of somewhere between 22 and 31 percent (1982 to 1988) according to one early study, and 18 percent annually (1983 to 1989) in another.[8]

In the early 1990s, both computer and communications equipment price declines seem to have accelerated, but a substantial differential appears to have been maintained. Grimm's (1996) study of telephone switch prices shows prices declined faster—to an average decline exceeding 16 percent annually—over 1992 to 1996.[9] But PC prices ramped up to decline rates of about 30 percent annually (over 1989 to 1992) according to one study and 34 percent (over 1989 to 1994) in another.[10]

We know of no empirical studies of telephone switch prices after 1996 but observe other evidence suggesting that the gap between communications equipment and computer price declines continued to be substantial. Berndt and Rappaport (2001) show yet a further increase in the pace of price decline in PCs, to about 40 percent annually after 1994.[11] Doms synthesizes fragmentary evidence from a variety of sources to suggest that for communications equipment (including local area network [LAN] equipment, telephone handsets, transmission equipment, and other hardware, in addition to telephone switches), overall, quality-adjusted price declines between 1994 and 2000 were bounded between perhaps 6 percent and 11 percent annually (his "conservative" and "aggressive" assumptions). This compares with a computer price deflator (including all computing equipment, not just PCs) calculated by the Bureau of Economic Analysis that falls at about 21 percent annually over this same period.[12]

These continuing, persistent, very large differences in measured rates of price decline for computers and communications equipment over a thirty-year period are difficult to reconcile. Both computers and communications equipment are heavy users of semiconductor devices, yet prices for these two classes of equipment continue to move very differently, even in recent years. Early studies suggested that the lack of "convergence" in quality-adjusted price trends between computers and communications may have been due in large part to regulatory factors.[13] But with the break up of the

7. See Flamm (1989) and Grimm (1996).

8. See Berndt and Griliches (1993) and Berndt and Rappaport (2001).

9. See Grimm (1996).

10. See Berndt, Griliches, and Rappaport (1995) and Berndt and Rappaport (2001).

11. See Berndt and Rappaport (2001).

12. See Doms (2003). Current values for the BEA's price index for computers and peripheral equipment are published in table 5.3.4: "Price Indexes for Private Fixed Investment by Type" of the monthly *Survey of Current Business.* Historical data are available online at http://www.bea.gov/bea/dn/nipaweb/TableView.asp?SelectedTable=127&FirstYear=2002&LastYear=2004&Freq=Qtr.

13. See Flamm (1989) and Gordon (1990).

Bell System and deregulation of large parts of the communications market in the mid-1980s, the expanding boundaries of real competition in communications equipment markets and the rapid explosion of growth in the largely unregulated data communications and networking market in subsequent years, regulatory regimes seem a less plausible explanation for observed, continuing differences in rates of quality-adjusted price change between computer and communications equipment.

The other possibility that has been considered is that quality improvement in communications hardware is simply poorly measured. Mismeasurement of communications equipment prices has the same distorting effects on measurement of productivity improvement and economic growth that have been the case with computers.[14] But even with the improved measurement of quality-adjusted prices documented in recent studies, large differences between computers and communications remain.[15]

One possible resolution of this paradox is that the specific types of chips that are used in communications equipment show slower price declines than those used in computers. Semiconductors are actually a broad and diverse group of products. They are intermediate goods used in the production of other goods ranging from PCs to timers on household appliances to automotive ignition systems. The prices associated with the different types of chips used in these distinct types of applications are likely very different.

We construct and compare semiconductor input price indexes for the two industries and show that the price index of semiconductor inputs to the communications equipment industry does, indeed, decline at a slower rate than does that for the computer industry. Over the 1992 to 1999 period, input price indexes for the semiconductor devices used in communications equipment and in computers fell at a compound annual growth rate of 12 percent and 32 percent per year, respectively. Moreover, we find that these differences in input prices can more than explain the observed differences in the rates of decline in output prices.

We caution that much is omitted from this analysis. Other factors could have caused large changes in these end-use prices that may have more than offset, or been offset by, changes in semiconductor input prices. Likely candidates include significant differences in the importance of, and price trends for, other inputs to production (for example, disk drives and displays are important inputs to computer systems, but a relatively minor input in communications gear) and differences in the magnitude and impact of technical innovation originating within the industry itself (as opposed to innovation embodied in components purchased from other industries).

14. See Sichel (2001), Crandall (2001), and U.S. Congressional Budget Office (2001).

15. For example, Doms and Forman (2003) find that rates of decline for data communications and networking hardware in the 1990s remained significantly smaller than those for computers over the same period.

This last factor, of course, may also be tied to market structure and competitive conditions in the two sets of industries, another domain in which there may be significant differences.

In the next section, we describe the data and methods we used in constructing the input price indexes. In section 12.3, we undertake some illustrative decompositions of the role of semiconductor prices in explaining user industry price trends for computer and communications equipment. We provide concluding comments in section 12.4.

12.2 Construction of the Price Indexes

We construct chained-Fisher indexes of price change for semiconductor devices (denoted i) used in different end uses (denoted e). The familiar formula for a Fisher price index ($I^e_{t,t-1}$) that measures aggregate price change for end-use e over two adjacent periods ($t-1$ to t) is

(1) $$I^e_{t,t-1} = \left[\frac{\sum_i \omega^e_{i,t-1}(P^e_{i,t}/P^e_{i,t-1})}{\sum_i \omega^e_{i,t}(P^e_{i,t-1}/P^e_{i,t})}\right]^{1/2},$$

where the expenditure weights are given by

(2) $$\omega^e_{i,t} = \frac{P^e_{i,t}Q^e_{i,t}}{\sum_i (P^e_{i,t}Q^e_{i,t})},$$

and P and Q denote prices and quantities, respectively.

The index is a ratio of weighted averages that weigh the price change for each chip by its relative importance in the end use. While equation (1) measures price change for two adjacent time periods ($t-1$ to t), price change over longer periods of time (say, time o to time t) is measured by chaining the indexes for adjacent time periods together:

(3) $$P^e_{o,t} = \prod_{s=1,t} (I^e_{s,s-1})$$

To form these indexes, we need data on nominal shipments—for the weights—and on prices—to form the price relatives: $P^e_{i,t}/P^e_{i,t-1}$.

If the following two conditions occur, then input price indexes will vary across end uses: the end uses must use different types of chips, and the prices for those chips must show different rates of price change. As shown in the following, both of these conditions hold—and in a very significant way—in our data.

12.2.1 Nominal Weights

We obtained data on nominal shipments of semiconductor devices broken out by end use from a survey sponsored by the World Semiconductor

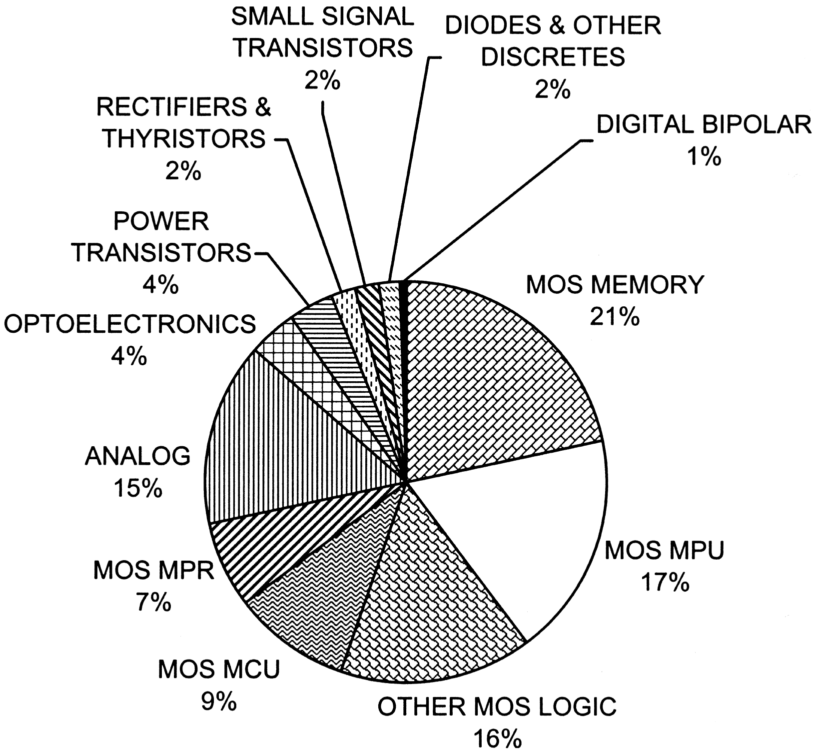


Fig. 12.1 Value of semiconductors consumed worldwide, by consumption product class, 1999

Source: Semiconductor Industry Association (2002).

Trade Statistics (WSTS) program, a cooperative venture sponsored by national semiconductor industry associations around the world. The survey provides data on shipments for twelve aggregate classes of semiconductor devices: five classes of metal oxide semiconductor (MOS) chips (MOS memory, MOS microprocessors, MOS microcontrollers, MOS microperipherals, and other MOS logic); two classes of other types of integrated circuits (analog and bipolar), and five types of single-function "discrete" semiconductors (power transistors, small signal transistors, thyristors and rectifiers, optoelectronics, and diodes and all other discretes).

The data for 1999 are summarized in figure 12.1. Note that much of the world chip market is made up of MOS devices—well-known chips like MOS memory chips (e.g., Dynamic Random Access Memory (DRAM) chips) and microprocessors (MPUs, like Pentium chips) and some less-visible MOS devices like microperipherals (MPRs) and microcontrollers (MCUs).[16]

16. See Semiconductor Industry Association (2002b) for a detailed descriptions of these devices and their capabilities.

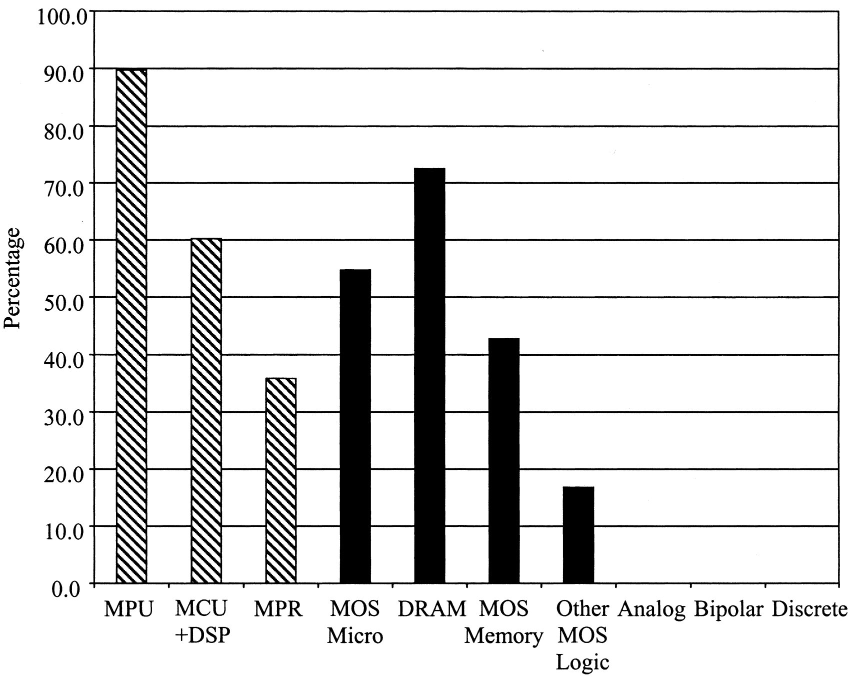


Fig. 12.2 Share of leading-edge wafers in total silicon area processed, by product, 1999

Source: Authors' calculations based on unpublished data on Semico Research wafer shipment data, obtained from International SEMATECH, Austin, Texas.

One important dimension along which these devices differ is the degree of "high techness." Researchers at the International SEMATECH research and development (R&D) consortium classify these product categories as "leading edge" or "non-leading edge" according to the manufacturing processes used when they are produced and the percentage of the wafers processed in that category that use the latest leading-edge processes. Figure 12.2 shows the share of total silicon wafer area processed in 1999 for several semiconductor device classes using this indicator. The solid bars correspond to more highly aggregated classes of products, while the striped bars correspond to more disaggregated product categories within the aggregates to their right (and note that the shares are of silicon area processed, not of value of product, within a category). According to this indicator, MOS microprocessors (MPUs) are 90 percent leading edge; MOS memory is a little under half leading edge; and microcontrollers, microperipherals, and other MOS logic at about 17 percent are even less dependent on leading-edge manufacturing. Analog, bipolar, and all discrete device categories are entirely produced with more mature technologies that are characterized as non-leading edge.

The analog category—making up 15 percent of world shipments in

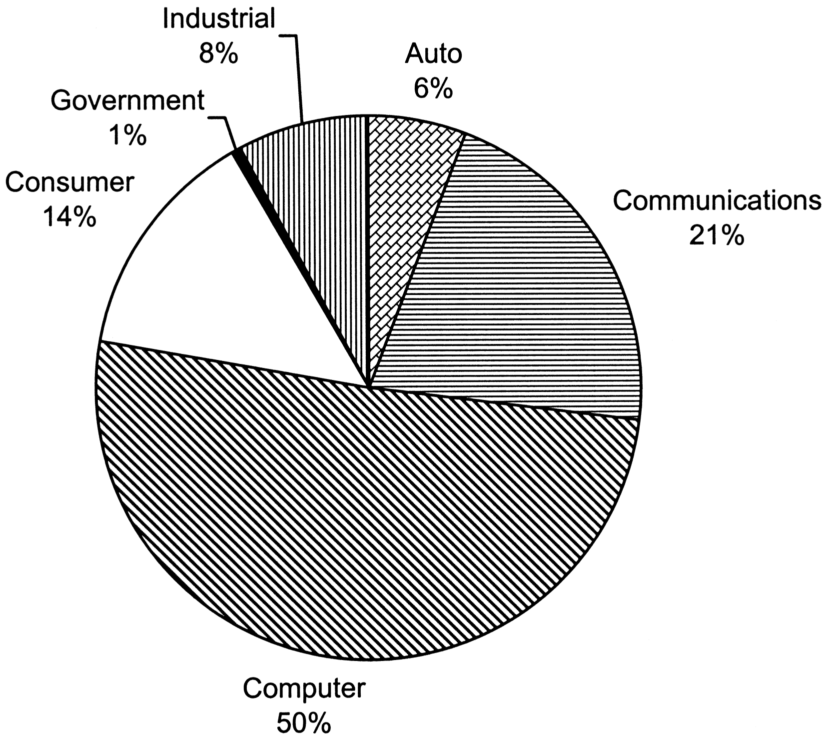


Fig. 12.3 Value of semiconductors consumed worldwide, by end-use sector, 1999
Sources: Semiconductor Industry Association (2002). WSTS End-Use Survey.

1999—is acknowledged within SEMATECH to be poorly characterized within this breakdown and to require further work. It is actually a combination of some very high-tech products produced with leading-edge technology and some relatively mature products produced with relatively old technology. Because analog chips are a major input to communications equipment, this topic is revisited in the following.

For each of these classes of semiconductor devices, nominal shipments are further broken out into the following end-use categories: computer, communications, consumer electronics, industrial, automotive, and government.[17] As shown in figure 12.3, the largest end use for semiconductor

17. The definitions for each end use are as follows: the *computer* category includes mainframes, peripherals, and PCs. *Communications* includes telecommunications, transmission, two-way, and cellular radio equipment. The remaining categories are fairly diverse. *Consumer* includes the following type of devices: entertainment, radio, TV, VCR, personal or home appliance, cameras, games, and so on; *automotive* represents chips used in auto entertainment, engine controls, and all other auto applications; the *industrial and instrument* category includes lab, test, control, and measurements; and chips used in *government* end uses include those in military and government special purchases.

chips is computers: about half of value of worldwide shipments in 1999 went to computer manufacturers. The next-largest end uses that year were communications equipment (21 percent) and consumer electronics (14 percent). Together, these three groups of end use industries accounted for about 7/8 of semiconductor consumption in 1999, while all other categories together accounted for the remaining 1/8 of shipments.

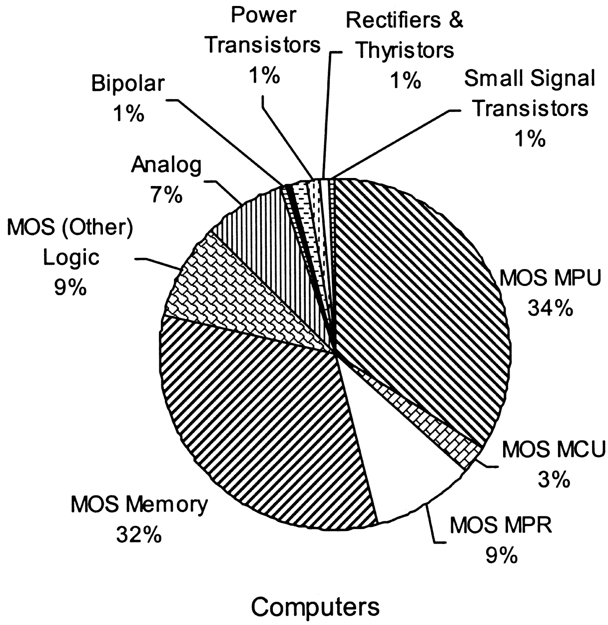
The disaggregate data show that the composition of semiconductor devices used in computers is very different from that of communications equipment. As shown in figure 12.4, the bulk—79 percent—of semiconductor shipments to computer makers are made up of MOS devices that are known to have experienced extremely rapid rates of technological change (memory and microcomponents: MPU, MCU, and MPR). These are the largest segments of the overall semiconductor market in volume and value (accounting for 56 percent of global semiconductor sales in 1999) and are the primary products produced using the most technologically advanced, leading-edge fabrication lines (see figure 12.2). The large volumes for these products are used to justify large fixed investments in deploying the most advanced, current manufacturing technology in their production.

In contrast, the composition of semiconductor devices used in communications equipment is much more diverse and more skewed toward devices where quality-adjusted price trends are less well understood. MOS memories and microcomponents make up only 34 percent of the semiconductor inputs to communications equipment; the next two largest classes of inputs are other MOS logic and analog devices, where significant technological change has also taken place. The remaining 15 percent of inputs are from older, more mature devices. Data for other years in the 1990s show a similar pattern. These differences in composition have implications for price measurement when the prices of individual devices change at different rates.

12.2.2 Price Relatives

Relative prices for individual devices ($P^e_{i,t}/P^e_{i,t-1}$) are empirically measured using price indexes. Because price indexes broken out by device *and* end use are not available, we assume that the measured price change for each device grouping does not vary by end use ($P^e_{i,t}/P^e_{i,t-1} = P_{i,t}/P_{i,t-1}$). This assumption is plausible for semiconductor devices that are largely commodity-like (for example, standard memory, logic, and microprocessor components), but is potentially problematic for devices that are customized for particular end uses.

Most of the price indexes we used are Fisher ideal matched-model indexes either taken from previous studies (Grimm 1998; Aizcorbe 2002; and Aizcorbe, Corrado, and Doms 2000) or recalculated by the authors from the sources used in those studies. For logic chips (accounting for 16 percent



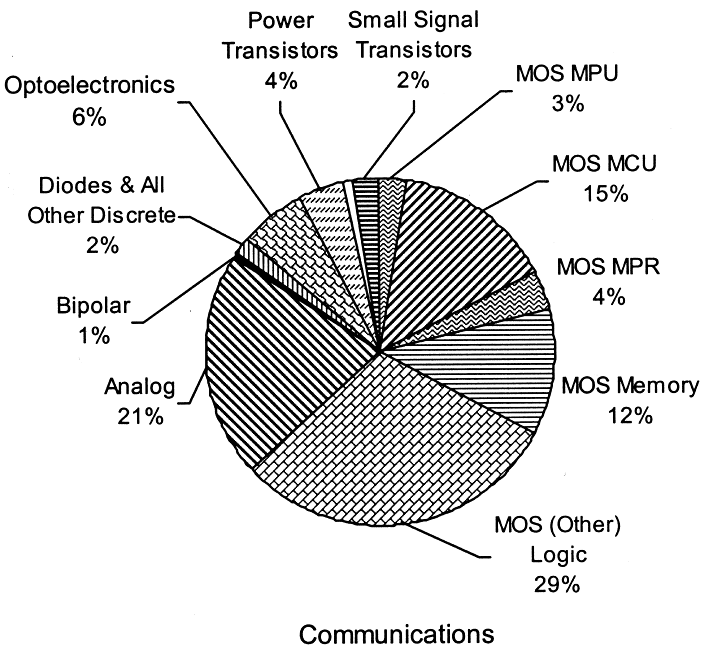


Fig. 12.4 Semiconductors used in the production of computers and communications equipment, by product class, 1999

Sources: Semiconductor Industry Association (2002). WSTS End-Use Survey.

of the market in 1999), detailed market share data were unavailable, and geometric means of price relatives for matched models were used instead (see table 12A.3). One important exception is the index for MPR chips. As detailed in the appendix, we use new data to construct an annual quality-adjusted Fisher price index to better capture the rapid technological improvements reported for these devices. The other notable exception is the price index for analog devices. As mentioned earlier, these devices are important in the production of communications equipment and are thought to have poorly measured price indexes. The appendix details the construction of the hybrid index we use for these devices; while we measure price change for the low-tech devices in this class using average sales prices at the lowest possible level of disaggregation, we assume that the price change for the high-tech devices in this class parallels that of devices in the "Other MOS logic" class of chips. To obtain the hybrid index, we average over the two indexes using Fisher weights.

All told, we have annual price indexes for twelve classes of semiconductor devices—one for each of the semiconductor classes in figure 12.1. Price measures for these devices—given in the first column of table 12.1—decline at substantially different rates over the 1992 to 1999 period. For the most part, differences in the rates of price declines exhibited by the devices are intuitively plausible. Devices normally associated with rapid rates of product innovation and technical change do, indeed, show rapid price declines: MOS microcomponents (MPUs, MCUs and MPRs), MOS mem-

Table 12.1 **Constant-quality price change and nominal weights for semiconductors in computer and communication equipment**

	Price change (CAGR), 1991–1999	Nominal shipments weight, 1999 (%)	
		Computers	Communications
MOS MPU	–52.3	33.9	2.5
MOS memory	–30.8	32.2	11.7
MOS MPR	–14.0	10.0	4.0
Other MOS logic	–13.2	9.0	30.3
MOS MCU	–7.5	2.6	14.8
Thyristors and rectifiers	–7.1	0.7	0.9
Power transistors	–5.6	1.1	4.2
Small signal transistors	–5.3	0.5	2.4
Optoelectronics	–3.6	1.6	6.0
Diode and all other discrete	–2.6	0.5	1.7
Digital bipolar	0.6	0.6	0.6
Analog[a]	1.4 (–9.0)	7.3	20.8

Source: Authors' calculations.

[a]The two price indexes for analog devices are referred to as the World Semiconductor Trade Statistics (WSTS) and Hybrid indexes, respectively.

Table 12.2 **Semiconductor input price indexes, by end use, 1992–1999**

	Compound annual growth rate		
	1992–1999	1992–1995	1995–1999
Worldwide			
Auto	–12.35	–3.97	–18.16
Communication	–15.33	–3.33	–23.34
Computer	–32.22	–11.30	–44.60
Consumer	–13.97	–2.27	–21.82
Government	–17.30	–3.00	–26.62
Industrial	–15.36	–3.36	–23.38
North America			
Auto	–12.46	–4.64	–17.91
Communication	–15.58	–3.41	–23.69
Computer	–34.74	–13.29	–47.26
Consumer	–15.22	–2.17	–23.85
Government	–14.74	–3.37	–22.39
Industrial	–16.11	–4.27	–24.02

Source: Authors' calculations based on table 12A.8 in the appendix.

ory chips, and Other MOS logic. Similarly, more mature chips that have not undergone much change in the last decade do not show much price decline, for example, bipolar devices.

The second and third columns of table 12.1 report the nominal shares data associated with each device. As may be seen, prices for semiconductor devices that go into computers tend to fall faster than those that go into communications equipment. Chips whose prices fall more than 30 percent account for about 65 percent of the nominal value of chips that go into computers. Prices of the remaining chips fall at much lower rates—14 percent or less—and have a much heavier weight in communications equipment.

As shown in the top panel of table 12.2, semiconductor input price indexes differ substantially across end uses.[18] For the period 1992 to 1999, input chip prices for automotive end uses decline the most slowly—declining at about a 12 percent compound annual growth rate (CAGR)—while those of computer chips decline the fastest—at about a 32 percent CAGR over the same period. Input prices for communications end uses fell at a 15 percent CAGR over the period—just a bit faster than prices for automobile end uses. The next two columns provide measures of price change for the pre- and post-1995 periods. In all cases, price indexes experience faster price declines after 1995 than in the earlier period. But, in either case, there

18. The robustness of these estimates to changes in the underlying assumptions is discussed in the appendix. Although the numerical results can be sensitive, the qualitative results are the same.

is always a substantial gap between the computer and communications equipment indexes.

The indexes discussed thus far use worldwide end-user consumption of semiconductors as weights. Alternatively, it is possible to use North American consumption of our twelve classes of semiconductor prices by end-user industry to construct input price indexes for specific U.S. industries. The results, shown in the bottom panel of table 12.2, are very close to those shown in the preceding, reflecting the fact that the mix of semiconductors used in U.S. end-use industries is roughly identical to the mix overseas. Economically, this is a consequence of the fact that semiconductors are sold in what is effectively an integrated global market, with transport costs for this very light and compact product too small relative to the value of the product, to create shelter for regional differentials in prices that might otherwise lead to substitution among device classes and differences in semiconductor input mix across countries.

12.3 Contribution of Changes in Semiconductor Input Prices to Changes in Output Prices

We have concluded that differences in the composition of semiconductor inputs used in computer and communications equipment account for significant differences in the rate at which the prices of semiconductor *inputs* used in these two industries fell through the 1990s. We can now examine the importance of semiconductor prices for prices of the *end goods* produced by the user industries purchasing these inputs.

Our first step is to sketch out a simple analytical framework. We shall assume constant returns to scale in the production of electronic goods that make use of semiconductors and allow for imperfect competition and technological change in their using industries. We approximate short-run marginal cost with a unit variable cost function.[19] Conceptually, we have in mind a monopolistic competition model of the market for these electronic products, where every producer makes a unique variation of the basic industry product and therefore faces a downward-sloping demand curve. Profit maximization then yields a price-marginal cost margin that is inversely proportional to the producer's perceived price elasticity of demand. In the long run, as the effects of entry or exit from the industry and conse-

19. See Morrison (1992) for an extended discussion of a decomposition of price change into its component elements based on variable cost function and Oliner and Sichel (2000) for a similar framework. Note that our assumption of constant returns to scale is inessential; with nonconstant returns to scale, a scale effect must also be incorporated into our decomposition of price change. This decomposition is derived from cost functions and is dual to a productivity growth decomposition derived from a production function. For discussion, see Basu and Fernald (1997).

quent shifts in demand curves are felt, the price-marginal cost margin will adjust so that no economic profits are being earned.

Adopting these assumptions, we can write

$$P^e = (1 + \mu)g(P_s, \mathbf{P}'_z; \mathbf{k}', t), \tag{4}$$

where P^e is the price of output for some given industry (or end use), μ is the markup of price over unit variable cost $g(\cdot)$, reflecting both imperfect competition and subequilibrium (short-run capital per unit of output diverging from the long-run optimum). Costs are a function of the semiconductor input price for that industry, P_s, a vector of all other relevant input prices, $\mathbf{P}'_z$, a vector of fixed (in the short run) capital inputs per unit of output, $\mathbf{k}'$, and an index representing the possible impact of technological changes and other factors shifting the unit variable cost function over time, t. Taking logs on both sides of this equation and differentiating with respect to time, we have

$$\begin{aligned}\left(\frac{dP^e}{dt}\right)\left(\frac{1}{P^e}\right) = \left(\frac{1}{1+\mu}\right)\left[\frac{d(1+\mu)}{dt}\right] + \left(\frac{1}{g}\right)\left(\frac{\partial g}{\partial P_s}\right)\left(\frac{dP_s}{dt}\right)\\ + \sum_{i \neq s}\left(\frac{1}{g}\right)\left(\frac{\partial g}{\partial \mathbf{P}_{zi}}\right)\left(\frac{d\mathbf{P}_{zi}}{dt}\right) + \sum_{j}\left(\frac{1}{g}\right)\left(\frac{\partial g}{\partial k_j}\right)\left(\frac{dk_j}{dt}\right)\\ + \left(\frac{1}{g}\right)\left(\frac{\partial g}{\partial t}\right).\end{aligned} \tag{5}$$

Making use of Shepherd's lemma, and the empirical approximation of $(dX/dt)(1/X)$, by the annual percentage rate of change (Δ), we then have, approximately,

$$\Delta P^e = \sigma_s \Delta P_s + [\Delta(1+\mu) + \sum_{i \neq s} \sigma_{zi}\Delta \mathbf{P}_{zi} + \sum_j \varepsilon_j \Delta k_j + \Delta g], \tag{6}$$

where σ is the variable cost share of an input, ε_j is the elasticity of variable unit cost with respect to fixed factor k_j, and changes in g measure technical change. In effect, we have partitioned the annual percentage change in the price of the output of a semiconductor input-using industry into the effect of semiconductor prices (the first term on the right-hand side) and the sum of all other effects (the terms in brackets). These residual determinants of output price changes not accounted for by semiconductor inputs, we note, are likely to be quite important, reflecting changes in markups over variable cost (which we would expect to be affected by demand swings in these highly cyclical industries, as well as transitory entry and exit by competitors, and secular trends in market structure), other production costs, and changing technology in the user industries.

Our strategy is simply to calculate the first term on the right-hand side of this last equation ($\sigma_s\Delta P_s$) and view it as the contribution of semiconduc-

Table 12.3 **Derivation of semiconductor cost share and contribution to output price change (%)**

		Semiconductor cost share					Contribution (percentage points) (5) = (4) × (1)	
	Price change[a] (1)	Shipment share[b] (2)		Shipments/ Variable cost[c] (3)	Semi inputs/ Variable cost (4) = (2) × (3)			
		Low	High		Low	High	Low	High
Consumer audio	–30.4	11	15	125.9	14.0	18.7	–4.3	–5.7
Computers	–52.7	20	30	150.8	30.6	45.1	–16.1	–23.8
Communications	–31.6	11	19	168.2	18.2	31.6	–5.7	–10.0

[a]Calculations based on appendix table 12A.8, percent change from 1997–1998.

[b]Calculations based on appendix table 12A.7.

[c]Calculated as shipments/(shipments – value added + payroll) using data from U.S. Census Annual Survey of Manufactures, 1998, for NAICS 3341 (computer and peripheral equipment manufacturing), NAICS 3342 (communications equipment manufacturing), NAICS 3343 (audio and video equipment manufacturing).

tors to the overall price change for semiconductor-using output (ΔP^e). Changes in the industry-specific price indexes for semiconductor inputs that we have just constructed ($\Delta \mathbf{P}_s$) are shown in the first column of table 12.3 for three sectors: consumer audio, computers, and communications. As noted earlier, these estimates—for changes from 1997 to 1998—document that the type of semiconductor chips that went into computers that year experienced more rapid price declines than those that went into the other two end uses.

The next three sets of columns indicate how we estimate the semiconductor cost share in variable cost (σ_s). We estimate this cost share in two steps. First, we gather together industry estimates[20] of the share of semiconductor inputs in the value of *shipments* of each end-use sector's electronic equipment—measured as $(P^sQ^s)/(P^eQ^e)$. Then, we use data from the Annual Survey of Manufacturers (U.S. Bureau of the Census 2000) to translate that share of shipments into a share of unit *variable* cost. Given the observed data, we actually approximate variable costs as shipments less nonlabor value added (i.e., the ratio of shipments/[shipments – value added + payroll] is multiplied by the semiconductor share of shipments).

A range of the available estimates for semiconductor content shares is given in the second set of columns of table 12.3; the full set of estimates is given in the appendix. Note that we suspect that estimates of semiconduc-

20. Measurement of the value of semiconductor input cost in different industries is a notoriously weak link in coverage of statistical agencies of the manufacturing sector (see Triplett [1996] for a more extensive discussion of these problems). Note also that these cost shares are for electronic equipment produced in each end-use sector—thus it is the semiconductor content of automotive electronic equipment, not the entire auto, that is being estimated.

tor cost shares are biased downward—electronic equipment shipments data (the denominator) often double-count sales of semifinished assemblies or rebranded equipment among manufacturers. We show both a low and high estimate here to place rough bounds on the industry estimates. The "high" estimates of semiconductor content represent a conservative choice for reasons just described. In either case, the semiconductor share of shipments is typically twice as large for computers than it is for the other two end uses.

Multiplying this share by the ratio of shipments to variable cost (table 12.3, column [3]) yields an estimate of the semiconductor content in variable cost for these industries (column [4]). Not surprisingly, the estimated shares are substantially higher for computers (30–45 percent) than for the other two end uses. Multiplying this estimate of semiconductor content by the change in the semiconductor input price index (column [1]) gives our estimate of the portion of the price change for each end use that can be attributed to changes in semiconductor input prices (the last column). Using our "high" estimates of semiconductor content, declines in semiconductor input prices pushed down computer and communications prices by about 24 and 10 percentage points, respectively.

But how large is this relative to the declines in end-use prices? That is, how much of the absolute *decline* in the end-use prices is explained by declines in semiconductor prices? Table 12.4 shows that price declines for

Table 12.4 Contribution of semiconductors to end use price change in 1998 (%)

		Contribution of semiconductors			
		Percentage points (2)		Share of end-use price change (2)/(1)	
	End-use price change (1)	Low	High	Low	High
Consumer audio[a]	–15.8	–4.3	–5.7	26.9	36.0
Computers[b]	–40.3	–16.1	–23.8	40.1	59.0
Communications					
LAN equipment[c]	–29.5	–5.7	–10.0	19.5	33.9
LAN equipment and switches[d]	–33.3	–5.7	–10.0	17.3	30.0

[a]Hedonic index with vintage included from Kokoski, Waehrer, and Rozaklis (2000), table 9.

[b]Matched model Fisher for all computer systems from Aizcorbe, Corrado, and Doms (2000).

[c]Corrado (2001, 139).

[d]Estimated as follows: Relative expenditure on switches, LAN equipment from Doms and Forman (2003) used as weights; weighted average of LAN equipment price change and estimated switch price change. Estimated switch price change taken as 1.258 times LAN equipment price change based on historical relationship between LAN and switch price change over 1992–1996 taken from Corrado (2001) and Grimm (1996).

semiconductor devices had a large impact on end-use prices. Column (1) gives estimates of quality-adjusted price change from 1997 to 1998 for three end goods: consumer audio electronics, computers, and communications equipment. The estimated effect of semiconductor prices is expressed in both percentage points—the second set of columns—and as a fraction of total equipment price change—the last set of columns. Our analysis suggests that semiconductors can account for roughly 40 to 59 percent of computer equipment price decline, roughly 27 to 36 percent of price declines for consumer audio, and maybe a little less for communications equipment in that year.

We can now address the puzzle originally posed: how much of the differential in computer and communication equipment price declines can be attributed to the respective differences in the contributions of semiconductors? To do this, we take the difference in the calculated price declines for communications and computers reported in table 12.4 and partition these differences into price change attributable to semiconductors versus the combined impacts of all other factors. Those numbers are reported in the top panel of table 12.5. The first column of table 12.5, for example, reports that quality-adjusted prices for computer equipment fell about 11 percentage points faster than LAN equipment in 1998. The second col-

Table 12.5 **Estimates of the relative contribution of semiconductors to price change in computers and communications equipment in 1998 (%)**

Change in computer prices less:	End-use price change[a] (1)	=	Semiconductor contribution[b] (2) Low	Semiconductor contribution[b] (2) High	+	All other factors (1) – (2) Low	All other factors (1) – (2) High
			Preferred measures				
LAN equipment	–10.8		–10.4	–13.8		–0.4	3.0
LAN equipment and switches	–7.0		–10.4	–13.8		3.4	6.8
			Alternate sales weights				
LAN equipment	–10.8		–7.3	–9.8		–3.5	–1.0
LAN equipment and switches	–7.0		–7.3	–9.8		0.3	2.8
			Calculations using natural logs				
LAN equipment	–22.1		16.0	–21.8		–6.0	–0.3
LAN equipment and switches	–18.3		16.0	–21.8		–2.2	3.5

[a]Calculated using figures in table 12.4, column (1); for the "Natural Logs" case, the calculations are based on an alternative calculation of the figures in table 12.4, column (1) that uses natural logarithms rather than percent changes.

[b]Calculated using figures in table 12.4, column (2); for the "Natural Logs" case, the calculations are based on an alternative calculation of the figures in table 12.4, column (2) that uses natural logarithms rather than percent changes.

umn documents that essentially all of that difference can be attributed to differences in the semiconductor contribution: the higher semiconductor contribution in computers accounts for between 10–14 percentage points of the 10.8 percent difference in computer and LAN equipment end-use price change. If one adds in switches to the communications price index (as in the second row of the table), the higher semiconductor contribution in computers more than explains the differences in end-use prices. We conclude that differences in semiconductor input price changes, coupled with differences in semiconductor intensity, can explain almost all of the difference between rates of decline of computer and LAN equipment prices in 1998.

The remaining panels in table 12.5 report two checks for the robustness of our analysis. First, we could have used a different model of competition in semiconductor-using industries. Although we do not find it particularly plausible in these high-tech sectors, we could have assumed perfect competition. In that case, the markup must equal zero, price would equal long-run marginal cost, and total costs would equal revenues. The analysis of equation (6) would continue to hold in all respects, except that σ_s would now represent the share of semiconductor inputs in revenues or sales, rather than variable costs, so we would now be using somewhat smaller weights to translate the impact of semiconductor price changes on computer and communications equipment costs. The second panel of table 12.5 demonstrates that this change would have no substantive impact on our conclusion, with virtually all of the difference in rates of decline in computer and communications equipment prices still explainable as the result of differing rates in semiconductor input price declines.

A second issue is our use of percentage rates of change to approximate the expression $(dX/dt)(1/X)$. Another equally credible approximation would be first differences in natural logarithms of X. For small changes, the two approximations should be quite close. For large changes, however (and some of our changes, exceeding 40 or 50 percent annually, are large), these two approximations could differ significantly. The bottom panel of table 12.5 shows that reworking our tables using first differences of logs (still expressed as a percentage, i.e., multiplied by 100) in lieu of percentage rates of change again leaves our conclusion unaltered. The difference in computer and communications equipment price declines is still entirely explainable by differing declines in semiconductor input prices.

Note, moreover, that the share of equipment price changes explained by semiconductor prices increases when using first differences of log prices in our decomposition. Semiconductors now account for 45 to 66 percent of computer price change from 1997 to 1998; 23 to 41 percent of LAN equipment and 21 to 36 percent of LAN equipment and switches; and 30 to 39 percent of consumer audio price changes.

12.4 Conclusions

This paper documents findings obtained from a first effort at calculating industry-specific semiconductor input price indexes and assessing the proportionate impact of changes in this high-technology input price on the prices and quality improvement in two equally high-tech industries downstream. The quality of data on semiconductor and computer prices is now acceptable for these purposes, but information on semiconductor input expenditures in all sectors and quality-adjusted price indexes in sectors other than semiconductors, computers, and a small fraction of communications equipment remains marginal. Given the available data, we were able to construct a decomposition for the year 1998, the only year where we felt we had relatively credible data on both semiconductor content and on the price indexes for both inputs and end-use outputs. Given these caveats, this initial analysis led us to two conclusions.

First, from 1997 to 1998, changes in semiconductor input prices appear to account for somewhere between 20 to 30 percent of price declines in both consumer electronics and LAN equipment and for 40 to 60 percent of price declines in computers. If we were to perform our decomposition using differenced logarithms instead of percentage rates of change in our approximations, the role of semiconductors in accounting for declining product prices would be even greater. Second, in 1998, computer prices fell between 7 and 11 percentage points faster than communications equipment, depending on our measurement of communications price changes. Differences in the quantity and composition of semiconductors used in these two sectors alone would have contributed perhaps 10 to 14 percentage points to this differential. To a first approximation, then (which is all we can reasonably expect given the poor quality of the available data), we conclude that differences in the composition of semiconductor input bundles coupled to significant differences in the relative importance of semiconductor inputs in cost together can potentially account for the entire difference in output price declines between the two sectors.

Appendix

Construction of the Semiconductor Input Price Indexes

Nominal Weights

We obtained data on nominal shipments of semiconductor devices broken out by end use from a survey sponsored by the World Semiconductor

Trade Statistics (WSTS) program, a cooperative venture sponsored by national semiconductor industry associations around the world. Under their auspices, the U.S.-based Semiconductor Industry Association has conducted an annual semiconductor end-use survey among U.S. users since 1984; since 1992, this survey has effectively covered all major semiconductor producers globally. The survey—administered to semiconductor producers participating in the WSTS program—asks respondents to classify their total worldwide sales by customer end-use market and geographic location. Sales numbers for nonparticipants in the WSTS program are imputed. The data we use cover the period 1991 to 1999 and report nominal shipments to both North American end users and all (worldwide) users.

The annual shipments (in thousands of units) for the world market are given in table 12A.1.

Nominal Weights for Microcomponents

An unfortunate feature of the data is that before 1995, industry consumption estimates for microprocessors (MPUs), microcontrollers (MCUs), and microperipherals (MPRs) are not reported separately—instead, they are lumped into one category called “MOS Micro.” For this earlier period, we assume the percentage breakdown among these subcategories within user industries of “MOS Micro” prior to 1995 was the same as in 1995.

Our results are not sensitive to this assumption. Table 12A.2 redoes table 12.2 in the paper employing an overall index for MOS Micro price aggregated across all user sectors over 1992 to 1994, in lieu of using a detailed sector-specific breakout of 1995 MOS Micro consumption as an approximation to weights for detailed (MPU, MCU, MPR) MOS Micro input price indexes prior to 1995. In the worldwide indexes, input chip prices for automotive end uses still experience the slowest declines, while computer chips still undergo the fastest—now –14 percent versus –31 percent CAGR over the period. Input prices for communications end uses still lies in between the two extremes, falling an average of –17 percent CAGR over the period to 27 percent of its 1992 level by 1999. The North American indexes show a similar pattern.

Interestingly, approximating sector-specific consumption bundles within MOS Micro prior to 1995 substantially widens the price decline gap between computers and other semiconductor-user sectors (table 12.2 in the text). This occurs because the specific type of MOS Microchip dominating computer use of these chips (MPU) fell much faster than other MOS Microchip types (MCU, MPR) over 1992 to 1995; these other chips dominated consumption of MOS Micro in other sectors. The net effect of crediting MPU price declines mainly to computers, and reducing the weight of MPU declines in price indexes for other sectors, is to leave noncomputer

Table 12A.1 **Nominal value of semiconductors consumed worldwide, by product class, 1992–1999 (in thousands of dollars)**

	1991	1992	1993	1994	1995	1996	1997	1998	1999
Diodes and all other discretes	1,341,463	1,290,629	1,498,533	1,747,473	2,465,981	2,189,285	2,262,636	2,144,643	2,429,508
Small signal transistors	1,803,269	1,783,320	1,979,948	2,432,565	3,309,019	2,884,870	2,756,933	2,374,300	2,752,609
Power transistors	2,489,270	2,629,819	3,015,544	3,704,908	5,181,568	4,936,068	5,083,619	4,616,964	5,404,166
Rectifiers and thristors	1,912,197	1,909,873	2,142,621	2,596,973	3,048,455	2,868,492	3,061,730	2,787,425	2,796,614
Optoelectronics	2,421,766	2,297,378	2,654,118	3,238,387	4,343,561	4,146,750	4,505,929	4,617,216	5,777,794
Digital bipolar	3,421,608	3,147,449	3,149,852	2,773,665	2,773,878	1,925,660	1,594,019	1,099,712	990,300
Analog	8,335,914	8,728,687	10,673,019	13,585,169	16,646,353	17,043,805	19,788,937	19,072,955	22,081,701
MOS MPU	3,565,035	5,460,259	8,589,686	10,995,486	14,278,592	18,529,996	23,466,929	24,775,645	27,191,405
MOS MCU	4,851,901	5,245,160	6,560,368	8,276,384	10,735,795	11,435,438	12,622,903	12,115,824	14,083,190
MOS MPR	2,971,576	3,205,239	3,921,409	4,548,201	8,381,534	9,862,276	11,676,920	10,449,901	10,426,667
Other MOS logic	9,260,355	9,331,793	11,857,716	15,529,061	19,781,034	20,125,581	21,047,471	18,564,413	23,158,467
MOS memory	12,233,100	14,835,353	21,266,867	32,450,325	53,457,910	36,018,211	29,335,095	22,993,001	32,286,130
Total semiconductor	54,607,454	59,864,958	77,309,681	101,878,593	144,403,681	131,966,433	137,203,120	125,611,999	149,378,551

Source: Semiconductor Industry Association (2002a).

Table 12A.2 Semiconductor input price indexes calculated using aggregate MOS Micro Price Index, by end use, 1992–1999

	Compound annual growth rate		
	1992–1999	1992–1995	1995–1999
Worldwide			
Auto	–13.66	–7.28	–18.16
Communication	–16.33	–5.96	–23.34
Computer	–31.33	–8.57	–44.60
Consumer	–15.14	–5.33	–21.82
Government	–17.80	–4.36	–26.62
Industrial	–15.61	–4.01	–23.38
North America			
Auto	–13.52	–6.92	–18.16
Communication	–16.54	–5.94	–23.69
Computer	–33.54	–9.53	–47.26
Consumer	–16.72	–6.15	–23.85
Government	–14.76	–3.90	–22.10
Industrial	–16.21	–4.52	–24.02

Source: Authors' calculations.

use semiconductor prices falling much less steeply over 1992 to 1995, while semiconductors used in computers fall even faster.

Price Relatives

Most of the price indexes we used for MOS devices are either taken from previous studies (Grimm [1998], Aizcorbe [2002] and Aizcorbe, Corrado and Doms [2000]) or recalculated from the sources used in those studies. Where quarterly or monthly indexes (rather than annual ones) are reported in these sources, a variant of a "superlative" procedure suggested by Diewert (2000) is used to aggregate up to an annual price relative.[21]

Table 12A.3 summarizes features of the underlying price indexes we use for semiconductor devices. In most cases, the price measures are Fisher indexes calculated from highly detailed data. With regard to index construction, Fisher indexes are available for all but 16 percent of the market: price change for subcategories of Other MOS logic chips are measured using

21. Our use of the Törnqvist-Theil index number formula given in Diewert (his formula 26) is to calculate (for annual price of a product in year 1 relative to year 0, based on monthly price data):

$$\ln P^1(p^0, p^1, s^0, s^1) = \sum_m \left(\frac{1}{2}\right)(s^{0,m} + s^{1,m}) \ln\left(\frac{p^{1,m}}{p^{0,m}}\right),$$

where $s^{i,m}$ is the share of expenditure on the product in question in month m in annual expenditure in year i, and subscript m refers to months. We have used this formula to construct annual price index relatives for adjoining years and then chained these to produce an index extending over the 1992 to 1999 period. See Diewert (2000, 9).

Table 12A.3 Price indexes for individual semiconductor devices: Underlying data

Type of device	1999 shares (%)	Index source	Price measure	Data frequency	Distinct devices	Time period
MOS						
Memory chips	21	2	Fisher	Q/Ave	84	1991–99
Microprocessors	18	1,3	Fisher	Q/Ave	85	1992–99
Microcontrollers	9	4	Fisher	M/Ave	5	1991–96
		2,4	Fisher	M/A/Ave	53	1996–99
Microperipherals	6	4	Fisher	A/Ave	5	1991–99
Logic chips	16	2				
General purpose logic			GeoMeans	A/end	35	1991–99
Gate array			GeoMeans	A/Ave	63	1991–99
Standard cell			GeoMeans	A/Ave	56	1991–99
Field programmable logic			GeoMeans	A/Ave	14	1991–94
Other integrated circuits, optoelectronics, and discrete devices	36	2,4	Fisher	M/Ave	43	1991–99

Sources: 1. Grimm (1998); 2. Aizcorbe (2002); 3. Aizcorbe, Corrado, and Doms (2000); 4. Authors' calculations.

Table 12A.4 Price indexes for the individual classes of MPR chips

Component price indexes	1991	1992	1993	1994	1995	1996	1997	1998	1999
Chipsets	118.1	100.0	100.4	80.9	102.4	124.4	79.5	76.6	42.3
Comm ICs	146.8	100.0	92.7	67.1	77.2	103.5	91.9	58.4	28.0
Graphics ICs	113.4	100.0	74.7	58.0	134.4	74.1	24.6	28.0	23.7
Mass storage	103.7	100.0	97.4	110.4	111.2	75.0	92.9	71.8	48.0
Voice and other	99.1	100.0	83.1	72.5	35.0	44.0	43.5	35.9	22.3
Fisher Ideal Index	116.8	100.0	88.8	73.0	99.6	97.9	65.8	57.5	35.0

Source: Authors' calculations.

geometric means or price changes because only price data were available at the subcategory level.[22] With regard to the underlying data, the quality of the data is not uniform: some indexes—like microprocessors—are built from very detailed data—eighty-five or so types of chips. At the other extreme, about 36 percent of the market—at the bottom of table 12A.4—is measured using only forty-three classes of chips. As is well known, as the data become more coarse, it becomes less likely that the quality of chips in

22. The formula for a geometric mean of price change from time $t-1$ to time t is

$$I_{t,t-1} = \prod_i \left(\frac{P_{i,t}}{P_{i,t-1}} \right)^{1/2}.$$

each class can be held constant over time, and price declines that signal technical change become confounded with price increases that reflect increases in quality. Similarly, some indexes are built using high-frequency data (monthly or quarterly), while other use annual data. While most measures are averaged over the reported period, the prices for general-purpose logic are year-end prices (the only way these data are reported).

For microcontrollers from 1996 through 1999, a synthetic Fisher ideal index based on WSTS unit values for digital signal processors (DSPs) and Aizcorbe's (2002) index for microcontrollers (excluding DSPs) over this period was constructed.

Adequate measures were not available for two types of devices. We filled in the gaps by comparing price movements for devices with missing periods with price movements in other categories when prices were available, then selecting the closest fit. For field programmable logic chips, adequate indexes are not available for 1995 to 1999, and we assumed that prices of these devices moved like a subindex of Other MOS logic excluding it (i.e., a Fisher index based only on General Purpose Logic, Gate Array, and Standard Cell devices) over 1995 to 1999. Indexes for microcontrollers were not available for the period before 1996. In that case, we used an average sales price available from the WSTS survey—the only available data.

Because indexes for MPUs were only available beginning in 1993, estimates in Grimm (1998) were used to extend the microprocessor index back in 1991.

Table 12A.5 provides annual price indexes for all the devices. Two of these product classes required special treatment. We detail the methods and sources for those two indexes next.

Special Index for Microperipherals (MPR)

This index assumes chip quality is proportional to the number of transistors and other electronic components contained in a chip. The index effectively measures the price per two-dimensional feature (e.g., transistor) on a MOS microperipheral (MPR) chip. The starting point was WSTS data on the value of sales, and number of units sold over 1991 to 1999 for five classes of chips included within MOS MPR: chipsets, communications integrated circuits (ICs), graphics ICs, mass storage ICs, voice and other ICs. Using data from Semico Research, SEMATECH has estimated the average line width per feature etched on each of these different types of chips and the average area of each of these classes of chips. Squaring line width gives an index of the minimum size for an electronic component etched on the surface of a chip, and dividing average chip area by this index yields an estimate of the maximum number of electronic components that fit on a chip with that area. Dividing average sales price per chip by the total number of electronic components then gives us an average price per electronic

Table 12A.5 Annual Fisher Ideal Price Index, by product class, 1992–1999

	1991	1992	1993	1994	1995	1996	1997	1998	1999	CAGR (1991–99)
MOS MPU	1.52	1.00	0.69	0.47	0.19	0.07	0.033	0.010	0.00	–52.32
MOS memory	1.30	1.00	0.97	0.98	0.93	0.45	0.20	0.08	0.07	–30.76
MOS MPR	1.17	1.00	0.89	0.73	1.00	0.98	0.66	0.57	0.35	–13.98
Other MOS logic	1.11	1.00	0.96	0.90	0.84	0.72	0.66	0.43	0.36	–13.16
MOS MCU	0.98	1.00	1.01	0.99	1.00	0.87	0.70	0.60	0.53	–7.48
Thyristors and rectifiers	1.00	1.00	0.98	1.00	0.97	0.77	0.69	0.63	0.56	–7.09
Power transistors	1.07	1.00	1.00	1.03	1.04	0.88	0.74	0.66	0.67	–5.65
Small signal transistors	1.05	1.00	1.04	1.05	1.06	1.00	0.82	0.70	0.68	–5.27
Optoelectronics	0.91	1.00	1.01	1.01	1.04	0.94	1.00	0.70	0.68	–3.63
Diode and all other discrete	0.98	1.00	0.98	1.01	1.16	1.06	0.93	0.82	0.79	–2.60
Digital bipolar	0.87	1.00	1.08	1.12	1.08	0.93	0.73	0.71	0.92	0.57
Analog	0.95	1.00	1.07	1.16	1.23	1.27	1.18	1.09	1.06	1.40
WSTS										
All analog	0.95	1.00	1.07	1.16	1.23	1.27	1.18	1.09	1.06	1.40
Low-tech	1.00	1.00	1.07	1.21	1.23	1.20	1.09	1.04	1.05	0.63
High-tech	0.92	1.00	1.07	1.13	1.24	1.30	1.18	1.07	1.02	1.22
Hybrid	1.07	1.00	1.00	1.00	0.95	0.85	0.78	0.57	0.50	–8.99
Other MOS logic	1.11	1.00	0.96	0.90	0.84	0.72	0.66	0.43	0.36	–13.16

Source: Authors' calculations.
Note: CAGR = compound annual growth rate.

component on a chip, which we interpret as a quality-adjusted price index within each of our five classes of MPR chips.

We then calculate WSTS revenue share data and price relatives for each of these five classes of MPR chips over the 1991 to 1999 period. Construction of a Fisher ideal price index for the MPR chip category is straightforward, using equation (1) in the text. As shown in table 12A.4 the resulting Fisher index falls substantially over this period, to less than one-third of its 1991 value by 1999.

Special Index for Analog Devices

We next detail construction of the hybrid index we use for these devices. While we measure price change for the low-tech devices in this class using the available WSTS unit value data, we assume that the price change for the high-tech devices in this class parallels that of devices in the "Other MOS logic" class of chips and average over the two indexes using Fisher weights to obtain the hybrid index.

Table 12A.6 compares alternative assumptions to measure price change of analog devices. The measure labeled "WSTS" is constructed using the

Table 12A.6 Alternative price indexes for analog devices, 1992–1999

	Compound annual growth rate		
	1991–1999	1991–1995	1995–1999
WSTS			
All analog	1.40	6.85	–3.77
High tech	1.22	7.67	–4.83
Low tech	0.63	5.36	–3.88
Hybrid index	–8.99	–2.86	–14.73
Other MOS logic	–13.16	–6.76	–19.13

Source: Authors' calculations.

very coarse WSTS data: the index is an annual Fisher index derived from monthly average unit sales prices for between five to eleven classes of analog chips, depending on the time period. This can safely be viewed as a conservative estimate of price declines for these devices.

At the other extreme, the measure labeled "Other MOS Logic" assumes the deflator for analog devices is equal to the deflator for other MOS logic—a category of MOS semiconductor chip with price declines intermediate between the highest volume, leading-edge technology used in memory and microprocessors and the relatively mature technology used in non-MOS devices and discrete semiconductors.

The hybrid index is a Fisher index of two Fisher indexes. The index for high-tech analog devices uses the Fisher index for other MOS logic to represent price change; the index for low-tech analog devices is a Fisher index of a low-tech subset of WSTS analog product categories (shown in line 3).[23] We believe this index is likely to be a better approximation to reality.

Annual measures corresponding to the alternative cases are given in table 12A.5.

Calculations for the Relative Importance of Semiconductor Inputs

Recall that we estimate the semiconductor share of variable cost in two steps. First, we gather together industry estimates of the share of semiconductor inputs in the value of *shipments* of each end-use device. Then we employ data from the Census Bureau's Annual Survey of Manufacturers (U.S. Bureau of the Census [2000]) to translate semiconductors' share of shipments into their share of unit *variable cost.*

23. Low-tech analog chips are those included in the WSTS categories for amplifiers, interface, voltage regulators and references, and data conversion circuits; high-tech analog chips are those in the special consumer circuits, comparators, and other linear devices categories.

Table 12A.7 **Estimates of semiconductor content as percentage of value of product**

	1998	1999	2000
Automotive			
DQ Cons/DQ Eqp		18	21
WSTS/EIO	16	19	
WSTS/DQ Eqp	15	15	17
Communications			
DQ Cons/DQ Eqp	11	17	19
WSTS/EIO	11	13	
WSTS/DQ Eqp		12	16
Computers			
DQ Cons/DQ Eqp		26	30
WSTS/EIO	20	23	
WSTS/DQ Eqp	22	24	26
Consumer Electronics			
DQ Cons/DQ Eqp		13	15
WSTS/EIO	11	12	
WSTS/DQ Eqp	11	11	15
Government			
DQ Cons/DQ Eqp		4	5
WSTS/EIO	2	1	
WSTS/DQ Eqp	2	2	2
Industrial			
DQ Cons/DQ Eqp		9	0
WSTS/EIO	8	8	
WSTS/DQ Eqp	9	8	10

Sources: Semiconductor consumption by user sector: DQ Cons—Dataquest-Gartner Group, Semiconductor Product Trends in 2000, 7/31/2000 (Olsson 2001); WSTS—World Semiconductor Trade Statistics, Semiconductor Industry End-Use Survey (Semiconductor Industry Association 2002c). Value of equipment production by industry: DQ Eqp—Dataquest-Gartner Group, Semiconductor Product Trends in 2000, 7/31/2000 (Olsson 2001); EIO—*Electronic Industry Outlook, Fourth Quarter, 1998* (Electronics Outlook Corporation 1998).

Table 12A.7 pulls together a range of estimates of the semiconductor content of computers, communications equipment, and consumer electronics assembled from proprietary industry estimates and the WSTS semiconductor consumption estimates used in constructing our price indexes. The sources are denoted as follows: DQ Cons and DQ Eqp refer to Dataquest-Gartner Group, Semiconductor Product Trends in 2001, July 31, 2000; WSTS refers to the WSTS Semiconductor Industry End-Use Survey, various years; and EIO stands for the *Electronic Industry Outlook* (Electronic Outlook Corporation 1999).

This ratio of shipments to variable cost are based on data reported in the 1998 U.S. Annual Survey of Manufactures. We estimate the markup of shipment price over unit variable cost as shipments divided by shipments less nonlabor value added (i.e., shipments/[shipments – value added + payroll]).

Table 12A.8 Annual Fisher Ideal Price Index, by end use industry, 1992–1999

	Deflator							
	1992	1993	1994	1995	1996	1997	1998	1999
Worldwide								
Auto	1	0.96	0.92	0.89	0.72	0.59	0.45	0.40
Communication	1	0.97	0.94	0.90	0.69	0.54	0.37	0.31
Computer	1	0.91	0.83	0.70	0.39	0.22	0.10	0.07
Consumer	1	0.98	0.96	0.93	0.73	0.58	0.40	0.35
Government	1	0.98	0.96	0.91	0.65	0.48	0.32	0.26
Industrial	1	0.97	0.95	0.90	0.68	0.52	0.36	0.31
North America								
Auto	1	0.96	0.91	0.87	0.71	0.58	0.44	0.39
Communication	1	0.97	0.93	0.90	0.68	0.53	0.36	0.31
Computer	1	0.89	0.80	0.65	0.35	0.19	0.09	0.05
Consumer	1	0.98	0.95	0.94	0.70	0.53	0.37	0.31
Government	1	0.98	0.96	0.90	0.70	0.56	0.39	0.33
Industrial	1	0.96	0.93	0.88	0.67	0.51	0.35	0.29

Source: Authors' calculations.

Data Sources for End-Use Prices

We measured computer prices using the matched-model price indexes in Aizcorbe, Corrado, and Doms (2000). Although computers are relatively well measured now, quality adjustment of prices for communications equipment and consumer electronics is problematic. For communications equipment, we formed a crude measure of quality-adjusted communications equipment price change in 1998 using the available data. We started with the estimates of quality-adjusted LAN equipment prices for 1992–present that are now available from the Federal Reserve Board. (See also table 12A.8.) For the period prior to 1996, we examined hedonic estimates of digital switch prices reported in Grimm (1996). We then used the historical ratio between quality-adjusted price changes for digital switches and quality-adjusted LAN equipment price changes over 1992 to 1996, multiplied by LAN equipment price changes in 1998, as a crude estimate of switch price changes in 1998. Finally, we average switch and LAN equipment price changes using relative expenditure in 1998 as weights and use the resulting calculation as our measure of quality-adjusted communications equipment price change in 1998. (Note, however, that these two categories of equipment accounted for only 30 percent of communications equipment spending in 1998).[24]

To measure price change for the consumer electronics sector, we found only one study of quality-adjusted prices for consumer electronics with a

24. See Doms and Forman (2003), table 1.

methodology that seems roughly comparable to those for computers and communications.[25] That study pertains to consumer audio equipment only, and we can only hope that our consumer electronics prices are roughly comparable.

References

Aizcorbe, A. M. 2002. Price measures for semiconductor devices. FEDS Working Paper no. 2002-13. Washington, DC: Federal Reserve Board of Governors, January.

Aizcorbe, A. M., C. Corrado, and M. Doms. 2000. Constructing price and quality indexes for high technology goods. Paper presented at the CRIW-NBER Summer Institute, session on Price, Output, and Productivity Measurement, Cambridge, MA.

Aizcorbe, A. M., S. Oliner, and D. Sichel. 2003. Semiconductor price puzzles. Paper presented at the CRIW-NBER Summer Institute, session on Price, Output, and Productivity Measurement, Cambridge, MA.

Basu, S., and J. G. Fernald. 1997. Returns to scale in U.S. production: Estimates and implications. *Journal of Political Economy* 105 (2): 249–83.

Berndt, E. R., and Z. Griliches. 1993. Price indexes for microcomputers: An exploratory study. In *Price measurements and their uses,* ed. M. Foss, M. Manser, and A. Young, 63–89. Chicago: University of Chicago Press.

Berndt, E. R., Z. Griliches, and N. J. Rappaport. 1995. Econometric estimates of price indexes for personal computers in the 1990s. *Journal of Econometrics* 68 (1): 243–69.

Berndt, E. R., and N. J. Rappaport. 2001. Price and quality of desktop and mobile personal computers: A quarter-century historical overview. *American Economic Review* 91 (2): 268–73.

Cole, R., Y. C. Chen, J. A. Barquin-Stolleman, E. Dulberger, N. Helvacian, and J. H. Hodge. 1986. Quality-adjusted price indexes for computer processors and selected peripheral equipment. *Survey of Current Business* 66 (January): 41–50.

Corrado, C. 2001. Industrial production and capacity utilization: The 2000 annual revision. *Federal Reserve Bulletin* 37 (3): 132–49.

Crandall, R. 2001. Comments on Dan Sichel, "Productivity in communications: An overview of the issues," presented at Brookings workshop on Communications Output and Productivity, Washington, DC. http://www.brook.edu/es/research/projects/productivity/workshops/20010223/20010223.htm.

Diewert, W. E. 2000. Notes on Producing an Annual Superlative Index Using Monthly Price Data. University of British Columbia, Department of Economics, Discussion Paper no. 00-08.

Doms, M. 2003. *Communications equipment: What has happened to prices?* San Francisco: Federal Reserve Bank of San Francisco.

Doms, M., and C. Forman. 2003. Prices for local area network equipment. Working Paper no. 2003-13. San Francisco: Federal Reserve Bank of San Francisco.

Dulberger, E. 1993. Sources of price decline in computer processors. In *Price mea-*

25. See Kokoski, Waehrer, and Rozaklis (2000), table 9.

surements and their uses, ed. M. Foss, M. Manser, and A. Young. 103–24. Chicago: University of Chicago Press.

Electronics Outlook Corporation. 1998. *Electronic industry outlook, fourth quarter, 1998.* San Francisco: Electronics Outlook Corporation, January.

Flamm, K. 1989. Technological advance and costs: Computers versus communications. In *Changing the rules: Technological change, international competition, and regulation in communications,* ed. R. W. Crandall and K. Flamm, 13–61. Washington, DC: Brookings Institution.

———. 1993. Measurement of DRAM prices: Technology and market structure. In *Price measurements and their uses,* ed. M. Foss, M. Manser, and A. Young, 157–97. Chicago: University of Chicago Press.

———. 1996. *Mismanaged trade? Strategic policy and the semiconductor industry.* Washington, DC: Brookings Institution.

———. 1999. Digital convergence? The set-top box and the network computer. In *Competition, innovation and the Microsoft monopoly: Antitrust in the digital marketplace,* ed. J. A. Eisenach and T. M. Lenard, 255–90. Boston: Kluwer Academic.

———. 2001. Moore's Law and the economics of semiconductor price trends. Paper presented at NBER Productivity Program meeting, Cambridge, MA.

Gordon, R. J. 1990. Telephone transmission and switching apparatus. In *The measurement of durable goods prices,* 395–404. Chicago: University of Chicago Press.

———. 2000. Does the "new economy" measure up to the great inventions of the past? *Journal of Economic Perspectives* 14 (4): 3–22.

Grimm, B. T. 1996. Quality adjusted price indexes for digital telephone switches. Bureau of Economic Analysis. Mimeograph.

———. 1998. Price indexes for selected semiconductors, 1974–96. *Survey of Current Business* 78 (February): 8–24.

Irwin, D. A., and P. Klenow. 1994. Learning by doing spillovers in the semiconductor industry. *Journal of Political Economy* 102 (6): 1200–1227.

Jorgenson, D. W. 2001. Information technology and the U.S. economy. *American Economic Review* 91 (1): 1–32.

Jorgenson, D. W., and K. J. Stiroh. 2000. Raising the speed limit: U.S. economic growth in the information age. *Brookings Papers on Economic Activity,* Issue no. 1:71–150. Washington, DC: Brookings Institution.

Kokoski, M., K. Waehrer, and P. Rozaklis. 2000. Hedonic approaches to quality adjustment in the CPI for consumer audio products. Division of Price and Index Number Research Working Paper no. 344. Washington, DC: U.S. Bureau of Labor Statistics.

Morrison, C. J. 1992. Unraveling the productivity growth slowdown in the United States, Canada, and Japan: The effects of sub-equilibrium, scale economies and markups. *Review of Economics and Statistics* 74 (3): 381–93.

Norsworthy, J. R., and S. L. Jang. 1993. Cost function estimation of quality change in semiconductors. In *Price measurements and their uses,* ed. M. Foss, M. Manser, and A. Young, 125–55. Chicago: University of Chicago Press.

Oliner, S. D., and D. E. Sichel. 2000. The resurgence of growth in the late 1990s: Is information technology the story? *Journal of Economic Perspectives* 14 (4): 3–22.

Olsson, M. 2001. *Semiconductor product trends in 2000.* Dataquest-Gartner Group Report no. SCSI-WW-MT-0104. San Jose, CA: Dataquest-Gartner Group, September.

Semiconductor Industry Association. 2002a. *Historic year-end bluebook, 2002.* http://www.semichips.org/pre_statistics.cfm.

———. 2002b. Product definitions for billings. Semiconductor Industry Association Mimeograph. http://www.semichips.org/pre_stat.cfm?ID-31.
———. 2002c. *WSTS End-Use Survey.* http://www.semichips.org/pre_statistics.cfm.
Sichel, D. E. 2001. Productivity in communications: An overview of the issues. Paper presented at Brookings workshop on Communications Output and Productivity, Washington, DC. http://www.brook.edu/es/research/projects/productivity/workshops/20010223/20010223.htm.
Song, M. 2003. Measuring consumer welfare in the CPU market: An application of the pure characteristics demand model. Paper presented at NBER Productivity Program meeting, Cambridge, MA.
Triplett, J. E. 1989. Price and technological change in a capital good: A survey of research on computers. In *Technology and capital formation,* ed. D. W. Jorgenson and R. Landau, 126–213. Cambridge, MA: MIT Press.
———. 1996. High tech industry productivity and hedonic price indexes. Paper presented at OECD expert workshop, Industry Productivity, International Comparison and Measurement Issues, Paris. http://www.oecd.org/document/33/0,2340,en_2649_201185_1825441_1_1_1_1,00.html.
U.S. Bureau of the Census. 2000. *Statistics for industry groups and industries: 1998.* Report no. M98(AS)1. Washington, DC: U.S. Department of Commerce, February.
U.S. Bureau of Economic Analysis. 2004. *Survey of current business.* Washington, DC: U.S. Department of Commerce, May.
U.S. Congressional Budget Office. 2001. *The need for better price indices for communications investment.* CBO Report. Washington, DC: Congressional Budget Office, June.